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ORBITAL THERMAL ANALYSIS OF LATTICE-STRUCTURED SPACECRAFT USING COLOR VIDEO DISPLAY TECHNIQUES

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Abstract

A color video display technique is demonstrated as a tool for rapid determination of thermal problems during the preliminary design of complex space systems. A thermal analysis is presented for the lattice-structured Earth Observation Satellite (EOS) spacecraft at 32 points in a baseline non Sun-synchronous (60° inclination) orbit. Large temperature variations (on the order of 150 K) were observed on the majority of the members. A gradual decrease in temperature was observed as the spacecraft traversed the Earth's shadow, followed by a sudden rise in temperature (100 K) as the spacecraft exited the shadow. Heating rate and temperature histories of selected members and color graphic displays of temperatures on the spacecraft are presented.

Introduction

During the preliminary design of new and complex spacecraft configurations, it is necessary to determine potential thermal problem areas such as local hot spots, regions affected by large thermal gradients and areas experiencing severe thermal cycling. Since many of the future systems are on the order of hundreds of meters in size and will be constructed of lattice-work (truss-like) structures with a large number (thousands) of connecting members, this requirement takes on added impact. It is cost prohibitive to conduct detailed thermal-structural interaction analyses for all conceivable Sun-Earth-spacecraft orientations experienced throughout the orbital lifetime of the mission. Worse cases have to be identified to provide a tractable approach. A color video display technique has been demonstrated as a tool for rapid determination of thermal problems for more detailed analysis. The technique has been employed in the orbital thermal analysis of the lattice-structured Earth Observation Satellite (EOS) system.

The EOS system is being studied for Earth, oceanic, and atmospheric observational resource missions in the 1990's. The satellite system would use microwave radiometer measurements to provide information for crop yield forecasting, climate predictions, coastal productivity, hydrology, water

quality, and coastal dynamics. Such missions require day/night/all-weather operations, contiguous high resolution mapping, global coverage, and multi-parametric sensing, hence the need for a large microwave antenna with an accurately defined surface. The mission and performance requirements used in the studies of the EOS systems are outlined in Table I. Spacecraft design requirements dictated packaging for a single Shuttle launch to place the EOS spacecraft in a Sun-synchronous orbit with a 5-year lifetime. A pointing accuracy of ±0.07 degrees absolute is required for the Earth pointing spacecraft.

Numerous strutural design concepts (Refs. 1 to 5), both deployable and erectable, have been identified as candidates for the EOS spacecraft. The box-truss concept (developed by Martin Marietta Aerospace) possesses a number of attractive features, namely:

1) deployment is sequential and linear,
2) the truss support structure is inherently stiff, and
3) it can be packaged in a single Shuttle flight.

The box truss is also one of the more complex structural configurations and is the subject of this study. The box-truss concept is characterized by a series of cubes joined together to form the lattice-structure of the spacecraft. The fully deployed spacecraft is shown in Fig. 1, and consists of a 120-m by 60-m parabolic reflector, a 120-m-long support structure and a 30-m feed beam on the focal axis.

Surface accuracies on the order of ±6 mm are the norm for microwave radiometer missions. Although the antenna support structures would be composed of members with extremely low thermal expansion, the potential distortion of the large reflector due to large thermal gradients are very critical. The objectives of this research are to evaluate the thermal environment on the box-truss concept during an Earth orbit with particular emphasis on the entry into and exit from the Earth's shadow.

The thermal analysis was conducted with the Interactive Design and Evaluation of Advanced Spacecraft (IDEAS) computer-aided design and analysis program (Ref. 6)

EOS Mission and Spacecraft Description

Mission Definition

The EOS spacecraft was designed for multidiscipline missions. A group of compatible sensors share the large antenna spacecraft to obtain remote sensing data to achieve combined Earth, ocean and coastal zone, and atmospheric observations. The sensor package consists of microwave radiometers providing day/night and near all-weather observations in the 1 to 37 GHz region, as well as sensors operating in the visible and IR regions. Potential observations from large microwave radiometers include soil moisture, water surface temperature, salinity, pollutants, sea state, and ice boundaries.

Measurement requirements for Earth observation missions include day/night, all-weather operations, contiguous coverage, ground resolution of less than 1 km, revisit frequency from one visit per day to one visit per week, and experiment life greater than 5 years. The corresponding performance requirements of the spacecraft are listed in Table I.

Spacecraft Description

Lattice work or a combination of repeating structures and tension cable designs have been identified as ideal candidates for the structural support system of future large antenna systems. These concepts are lightweight, packaged simply, are easily deployed or assembed on orbit and are inherently stiff. The lattice concepts include repeating structures such as the tetrahedral truss, box-ring truss, and box truss. The radial rib is a repeating cantilevered system and the hoop-and-column typifies the tension stabilized concept. Finite-element models of these concepts are shown in Fig. 2. Each of these concepts has been the object of investigation for various space missions. The Microwave Radiometer Spacecraft (MRS) study of Refs. 1 and 2 investigated the use of tetrahedral truss concepts for a mission to measure soil moisture for global crop forecasting. All five concepts were studied and compared in Refs. 3 and 4 for Land Mobile Satellite System (LMSS) missions. The box truss represents one of the more complex structural configurations and was selected for the current analysis.

The antenna design for the EOS mission is based on a number of considerations. An offset fed reflector operating in a pushbroom mode reduces aperture blockage and minimizes scattered radiation. The aperture size is dictated by the lowest operating frequency, the spatial resolution requirement, and number of feed beams. A spherical/parabolic reflector provides a line focus for the multiple beams, such that each feed sees a specified spot on the reflector and, subsequently, a specified spot on the ground.

To match these considerations with the mission requirements of Table I, the box truss structural configuration of Fig. 1 was developed. The box truss geometry consists of a series of cubes (Fig. 3) joined together to form the lattice structure of the spacecraft. The individual cubes, 15 m on each side, are designed such that the horizontal tubes are hinged and fold against the non-folding vertical tubes for packaging. The deployment sequence for the box truss spacecraft (Ref. 5) is shown in Fig. 4. Pretensioned telescoping tapes extend from each corner (both in the plane of the faces and across the cube diagonals) to stabilize the deployed cube. Both the tubular members and the telescoping tapes are constructed of graphite. The deployed spacecraft consists of a 120-m by 60-m spherical/parabolic reflector, a 120-m-long feed support mast and a 30-m feed beam on the focal axis. The antenna surface is spherical in the 120-m direction (with a radius of 232 m) and parabolic in the 60-m direction, with a focal length of 116.1 m. The spacecraft is pitched forward 19.33° about the y-axis to align the spacecraft inertial axis perpendicular to the Earth.

Orbit Selection

Orbit and altitude selection is dependent on the mission requirements and influenced by practical considerations. Of the requirements for the EOS mission given in Table I, full contiguous ground coverage or mapping is a function of the orbit and instrument parameters and the revisit time is a function of altitude. The preferred orbit for the land missions is a Sun synchronous (98° inclination) orbit which provides near global coverage and enables data to be collected over the same region at the same local time of day.

However, for the present study a spacecraft baseline orbit (60° inclination, non Sun-synchronous with an orbital altitude of 720 km) was defined. A sketch of the orbit is shown in Fig. 5. Orbit angle, η, is measured from the point of intersection of the orbit plane and the equator, the starting point for the thermal analysis. Thermal measurements were made at 32 equally spaced points in the orbit ($\Delta\eta = 11.25°$) as shown in Fig. 5b. Due to the inclination and low altitude of the orbit, it is observed that the spacecraft lies in the Earth's shadow during a major portion of the orbit (approximately 38% of the orbit).

IDEAS Program

The thermal analysis of the box-truss concept is conducted with the Integrated Design and Evaluation of Advanced Spacecraft (IDEAS) computer-aided design and analysis program (Ref. 6), which was developed for rapid evaluation of systems concepts and technology needs for future advanced spacecraft such as large antennas, platforms, and space stations. The IDEAS program is an expansion of the Large Advanced Space Systems programs (Ref. 7) and consists of 40 technical modules and interactive graphics displays linked by the AVID data base management system (Ref. 8), as shown in Fig. 6.

A single analyst at an interactive terminal can rapidly model the structure and design and analyze the total spacecraft and mission. On-orbit environmental computational algorithms are coupled with design and analysis models for rapid evaluation of spacecraft design or competing designs.

The thermal analysis is conducted by the Thermal Analysis (TA) module, which computes the transient temperatures for each structural member at a given position in the spacecraft orbit. Heat sources include solar and Earth albedo, Earth radiation, solar radiation, and the member's reradiation of heat absorbed. Heating rates are computed for each member at 32 points in the orbit using the Earth, Sun, and spacecraft geometry data files and algorithms. The module then performs an integration of the heating rates from a beginning point in the orbit to the desired point in the orbit to yield the temperature of each structural member. A table of temperatures is created and stored for future reference and/or subsequent analysis. For the present study, the temperature data is displayed using color graphics in order to visualize the spacecraft's heating at various points in the orbit. Also, the heating rate histories for each member are displayed for more detailed analysis.

Orbital Thermal Analysis

A thermal analysis of the lattice-structured EOS spacecraft was performed to demonstrate the color video display techniques as a tool for rapid determination of thermal problems during the preliminary design of complex space systems. The thermal analysis was conducted at 32 equally spaced points during the baseline non Sun-synchronous 60° inclination orbit. During this orbit, the spacecraft is in the Earth's shadow for a maximum of 38% of the orbit. The hottest condition occurs when the maximum number of dish members are aligned normal to the Sun ($\eta \approx 19\text{-}1/2°$). This corresponds to the tilt angle of the spacecraft to align the spacecraft inertial axis perpendicular to the Earth.

Heating Rate Data

Transient heating rates are determined on each member of the structure from the balance of energy absorbed from the three heat sources and the reradiation of energy from the member. Each structural member is assumed to be isothermal; there is no radiation exchange or conduction between the members, and shadowing of members by other members or the reflector mesh is not considered. Thus, all structural members with an identical orientation would experience the same incident heating rate history. Likewise, the temperature response would be identical for elements with the same orientation and cross-sectional geometry. Heating rate histories for the horizontal surface tubes, vertical members, and horizontal and vertical cables are presented in Fig. 7 for the 720-km, 60° inclination non-Sun-synchronous orbit.

The heating rate on the longitudinal surface tube from all sources reaches a maximum of 2030 W/m^2 when the spacecraft is aligned between the Earth and Sun. The Earth thermal contribution to the total spacecraft heating is 250 W/m^2 throughout the orbit. As the spacecraft progresses about the orbit, the heating rate decreases to a value of 1600 W/m^2 at the point of entry into the Earth's shadow. The decrease is due primarily to the decrease in Earth albedo heating (dependent on orientation of spacecraft relative to the Earth). During passage through the Earth's shadow, the solar and Earth albedo heating goes to zero.

The heating rate history on a vertical tube in the feed beam is presented in Fig. 7(b). Due to the 19-1/2° tilt angle of the feed beam relative to the direction of flight (and subsequently to nadir), the vertical tubes are aligned perpendicular to the Earth-Sun line at η = 109° and 289°. Peak heating would occur at these points. A peak of 1700 W/m^2 is observed at a time of 1.35 hours (289°) but the spacecraft enters the shadow at .51 hours, prior to the orbit angle of 109°. The decrease to 500 W/m^2 at time .1 hour corresponds to an orientation where the vertical tubes are aligned parallel to the Earth-Sun line and the only contributions to heating are Earth thermal and Earth albedo.

Heating on the horizontal and vertical cables (Figs. 7(c) and 7(d)) show similar trends as the horizontal tubes, with the exception of the orbital location and magnitude of peak heating (function of spacecaft orientation).

Temperature Data

Temperature data on each member of the EOS spacecraft were obtained at 32 points in the baseline orbit. The data were converted to colors using the color video display technique using a color bar ranging from deep blue (180 K) to white (340 K) such that the spacecraft is displayed as a multicolor structure, as shown in Fig. 8. The figure shows a visualization of the spacecraft structural temperatures at six points in the orbit:

a) On Earth-Sun line, $\eta = 0°$,
b) Just prior to entry into Earth's shadow, $\eta = 112.5°$,
c) Just after entry into Earth'shadow, $\eta = 123.75°$,
d) At midpoint of Earth's shadow, $\eta = 180°$,
e) Just prior to exit from Earth's shadow, $\eta = 247,5°$ and,
f) Five minutes after exit from Earth's shadow, $\eta = 258.75°$.

To eliminate the motion variable, the spacecraft was held stationary in each figure and the Earth and Sun were allowed to rotate about the spacecraft. A sketch of the orbital plane with the location of the spacecraft at the time of the measurements is shown in the upper right corner. Since the orbit is so low (≈720 km), the orbital track is exaggerated to simplify visualization.

At the hottest point in the orbit (Fig. 8a), the maximum number of members are aligned perpendicular or near perpendicular to the Sun-Earth line, and the member temperatures range from 266 to 337 K. Just prior to entry into the Earth's shadow ($\eta = 112.50°$), the vertical members have changed orientation from parallel to perpendicular to the Earth-Sun line, and have increased temperature to slightly over 300 K and the horizontal members are cooling (Fig. 8b). During transit of the Earth's shadow (Figs. 8c through e), the entire spacecraft cools by radiation to 183 to 195 K at the point of exit. Note that the model depicts the gradual cooling in the shadow, instead of producing a step function decrease after the entry into the shadow. Fig. 8f shows the rapid rise in temperature during the first 5 minutes after shadow exit. Maximum and minimum temperatures on the spacecraft during the entire orbit are tabulated in Table II. The shadow portion of the orbit is identified.

The sudden temperature rise in the spacecraft members during the 5 minutes following the Earth's shadow was observed to be approximately 100 K for the hot members and 35 K for the colder members. To provide a more detailed look at this situation, 10 additional data points were taken at 1/2-minute intervals during the first 5 minutes after exit from the shadow, the coldest point in the orbit. All members have cooled to between 183 and 195 K (Fig. 9a). In the first minute after exit (Fig. 9b), the horizontal and vertical members experience a temperature rise of about 50 K to 247 K while the diagonal tapes increase less than 5 K. Maximum and minimum temperatures on the spacecraft during the exit from the Earth's shadow are tabulated in Table III.

A short stop-action movie was produced to demonstrate the color graphics techniques by graphically showing the temperature history of each member of the lattice-structured spacecraft during an orbital transit. To eliminate the motion variable, the spacecraft was held stationary, and the Earth and Sun were allowed to rotate about the spacecraft.

Conclusions

A color video display technique has been demonstrated as a tool for rapid determination of thermal problem areas during the preliminary design of future complex space systems. The technique is particularly valuable for lattice-type structures with large numbers (hundreds or thousands) of connecting members; these cases would be both time and cost prohibitive with current thermal analysis programs.

The technique was employed in an orbital thermal analysis of the lattice-structured Earth Observation Satellite (EOS) system. Transient heating rate and temperature data were obtained at 32 points in a non-Sun-synchronous, 60° inclination orbit and the temperature data is displayed using color graphics to visualize the spacecraft heating at various points in the orbit.

The horizontal surface tubes are aligned perpendicular to the Sun throughout the orbit (except during shadow transit) and the only heating variation is due to the decrease in Earth albedo heating as a result of spacecraft position relative to the Earth. The vertical tube heating reflects the parallel alignment to the Sun (heating decrease to 500 W/m^2) just after conjunction with the Earth and Sun. Peak heating would occur at η = 109° and 289° when the vertical tubes are aligned perpendicular to the Sun line (except that the spacecraft is in the Earth's shadow at η = 109 K).

Temperatures ranged from 185 K (in the shadow) to 334 K (at the point of peak heating). A maximum temperature gradient (element-to-element) of 85 K was observed as the spacecraft exited the Earth's shadow. A sudden rise of 100 K was observed on the horizontal and vertical members during the first 5 minutes after exit from the shadow.

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Table I. Mission and Performance Requirements.

a) Mission Requirements.

REQUIREMENTS	IMPLIES
DAY/NIGHT OPERATION	OPERATE LOWER FREQUENCIES (1-10 GHz)
GLOBAL COVERAGE	PASSIVE SYSTEM
MULTIPARAMETER SENSING	OPERATE AT VARIOUS FREQUENCIES
CONTIGUOUS MAPPING	WIDE GROUND SWATH ORBIT PARAMETERS
OPERATIONAL ENVIRONMENTAL MONITORING	
ALL WEATHER OPERATION	LOWER FREQUENCIES

b) Performance Requirements.

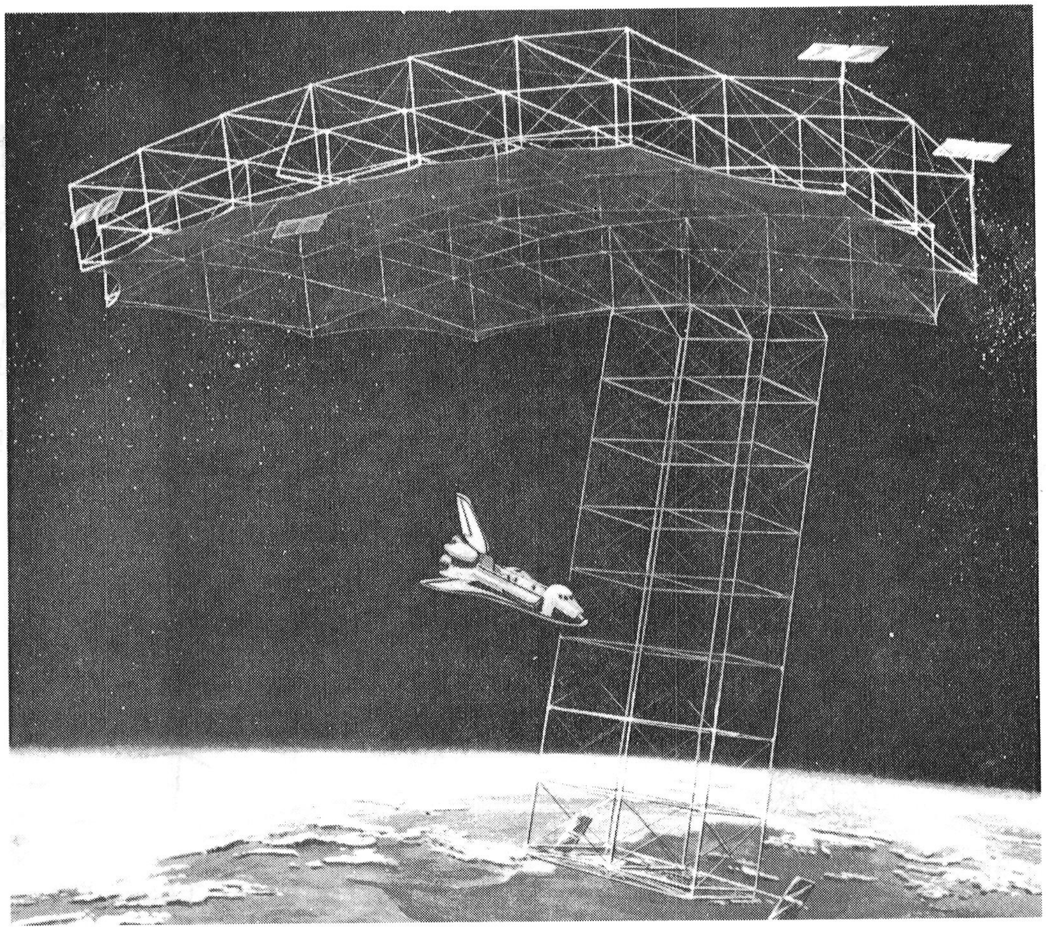
MEASUREMENT REQUIREMENT	PERFORMANCE REQUIREMENT
	RADIOMETER
6 MEASURANDS	3 FREQ. BANDS, APPROX. 1, 2, AND 4 GHz
LAND, WATER, ICE RADIATIONS	BRIGHTNESS TEMP. T_B, 200 TO 350 K
6 MEASURAND ACCURACIES	PRECISION, $\Delta T_B < 1$ K
RESOLUTION, <1 KM	BEAM WIDTH, $< 0.1°$ (ALTITUDE DEPENDENT)
COVERAGE, CONTIGUOUS	WIDE SWATH, >200 BEAMS
	ORBITAL PARAMETERS
EXPERIMENT LIFETIME, >5 YEARS	ALTITUDE MIN., 600 KM
REPEAT, 1/DAY TO 1/WEEK	ALTITUDE MAX., 1400 KM
COVERAGE - OVER FARM BELTS AND COASTAL ZONES	INCLINATION, 60° AND $\approx$98°
REPEAT PRECISION	ALT. DECAY, <0.1 SWATH/REPEAT EQUIV.

Table II. Temperature Data for Complete Orbit.

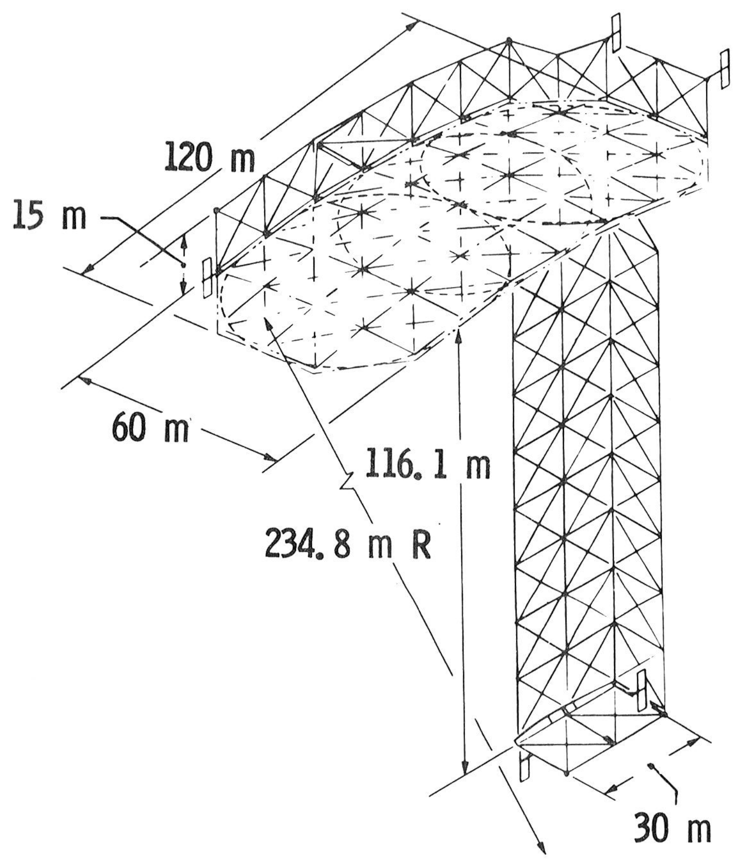
Orbital Position, radians		Temperature, ° K Max.	Min.
0.00		334	264
0.3927		334	259
0.7854		331	257
1.1781		325	253
1.5708		319	248
1.9635		316	237
	Enters at 2.010 rad.		
2.3562		243	212
2.7489		215	201
3.1416	Shadow	203	194
3.5343		198	188
3.9270		196	185
4.3197		195	183
	Exits at 4.371 rad.		
4.7124		299	218
5.1051		318	233
5.4978		326	250
5.8905		332	256
6.2831		334	264

Table III. Temperature Data at Exit from Shadow.

Time from exit, Min.	Orbital position, radians	Temperature ° K Max.	Min.
-0.05	4.3361	194	182
0.0	4.3710	209	192
0.5	4.4059	247	193
1.0	4.4408	245	193
1.5	4.4757	258	195
2.0	4.5106	276	198
2.5	4.5455	277	199
3.0	4.5804	282	203
3.5	4.6153	289	207
4.0	4.6503	293	211
4.5	4.6852	296	215
5.0	4.7124	299	218



a) Artist's Concept.



b) Box Truss Configuration.

Figure 1. EOS Spacecraft.

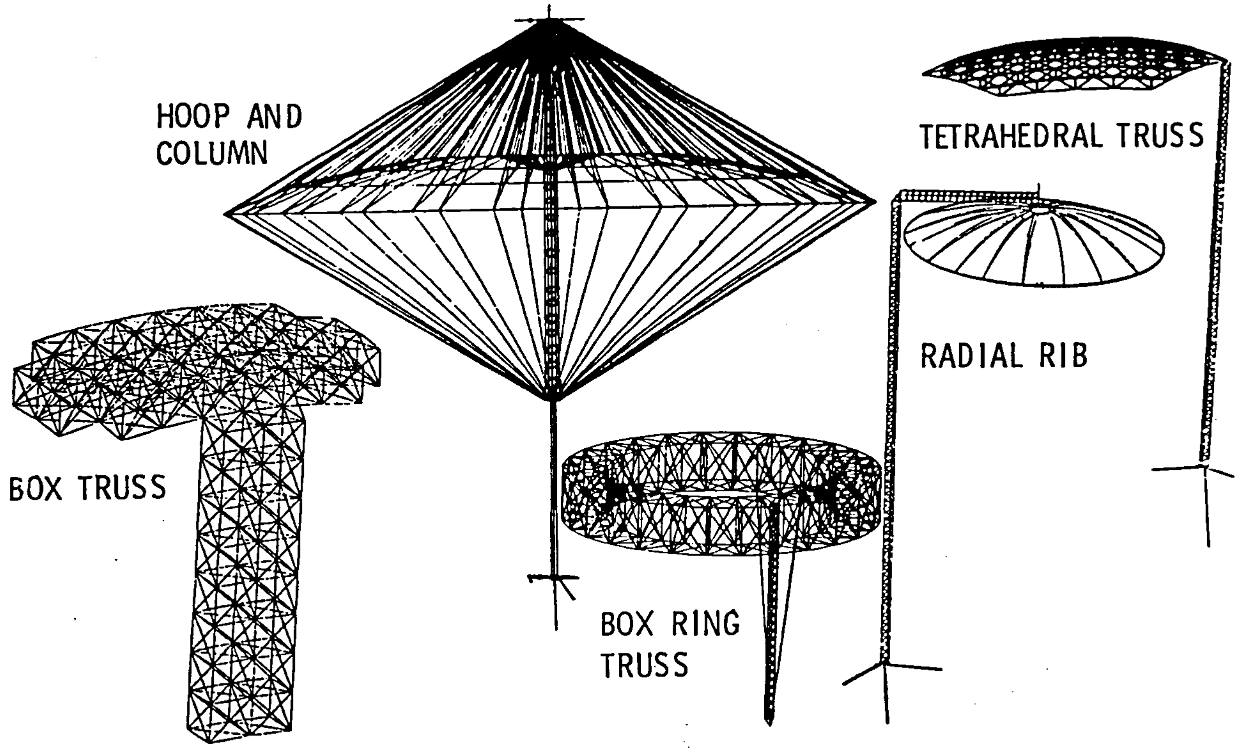


Figure 2. Antenna Structural Concepts.

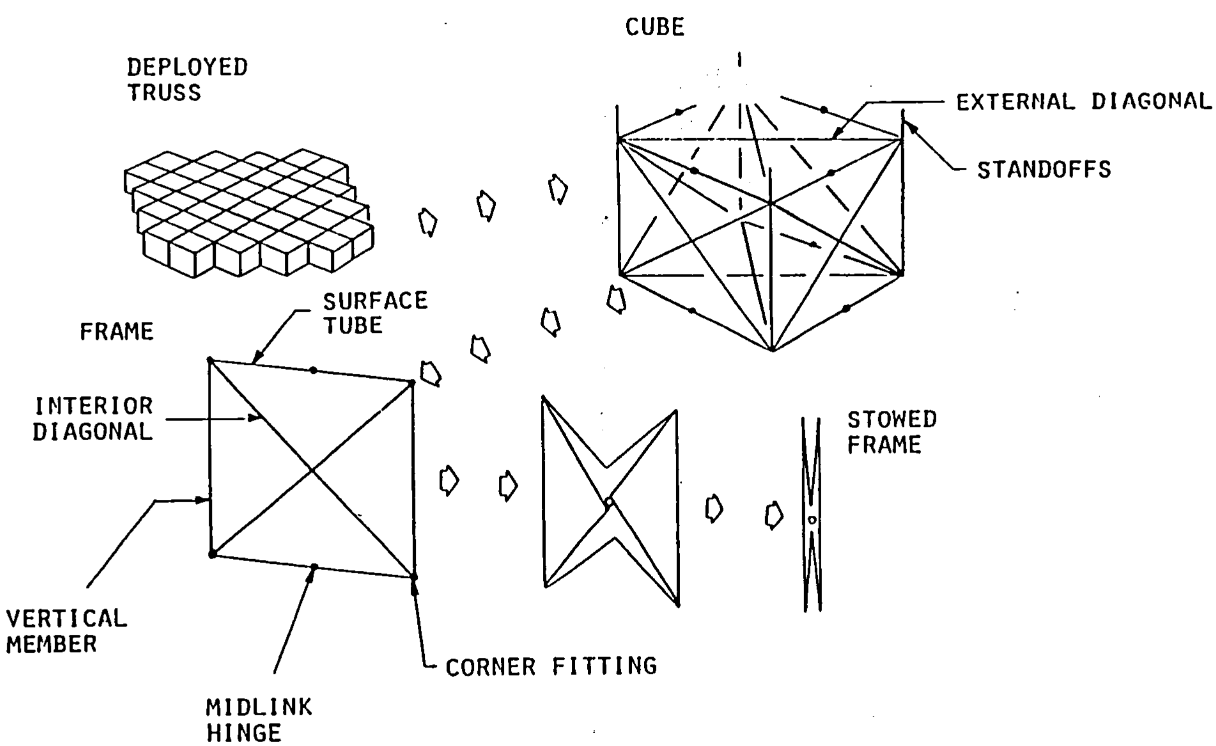


Figure 3. Box Truss Structural Elements.

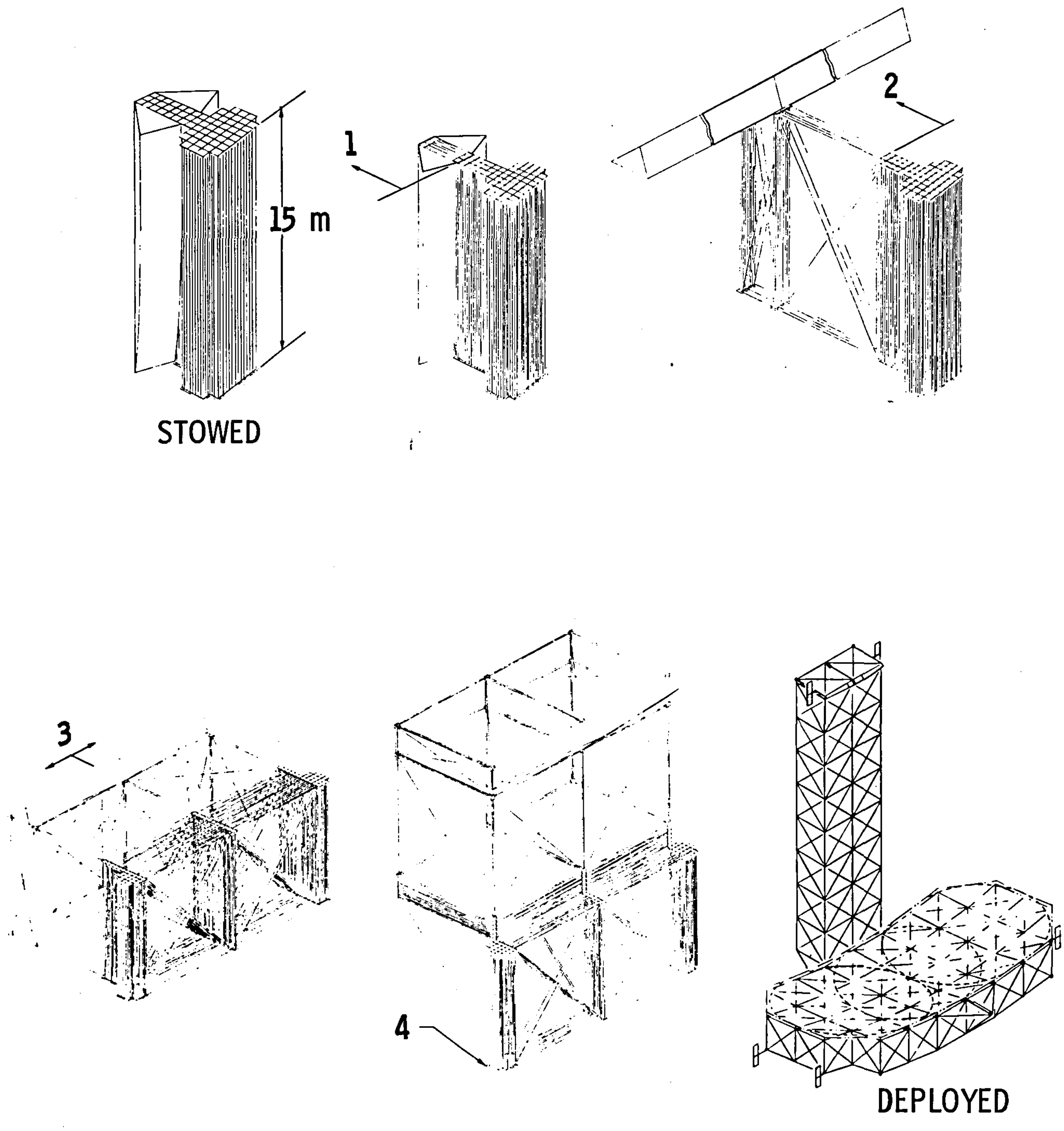
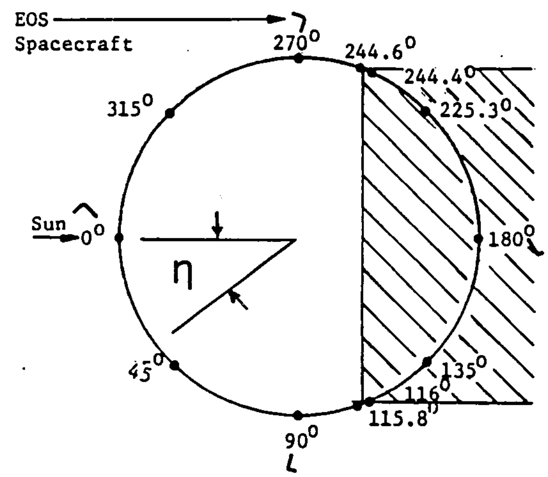


Figure 4. Deployment Sequence.



a) 60° Inclination Orbit Path.

b) Location of Thermal Analysis Measurements.

Figure 5. EOS Orbit.

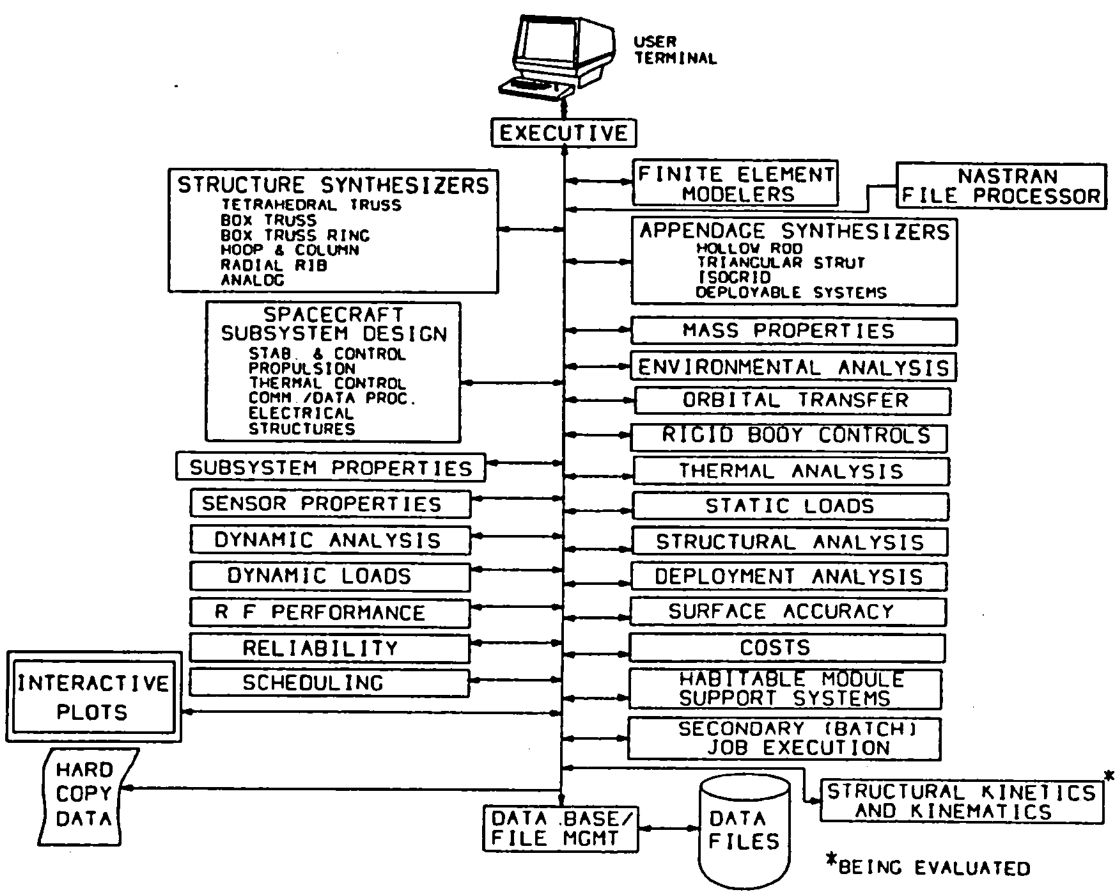
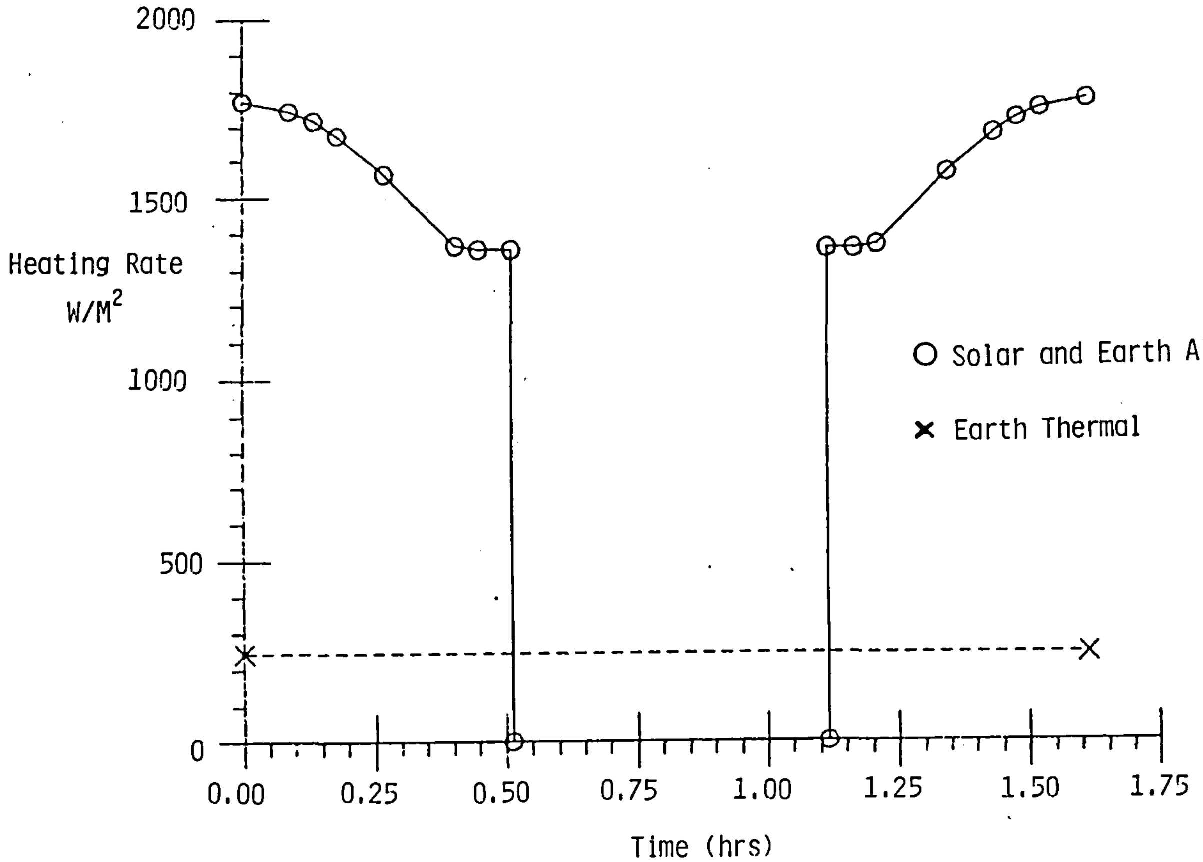
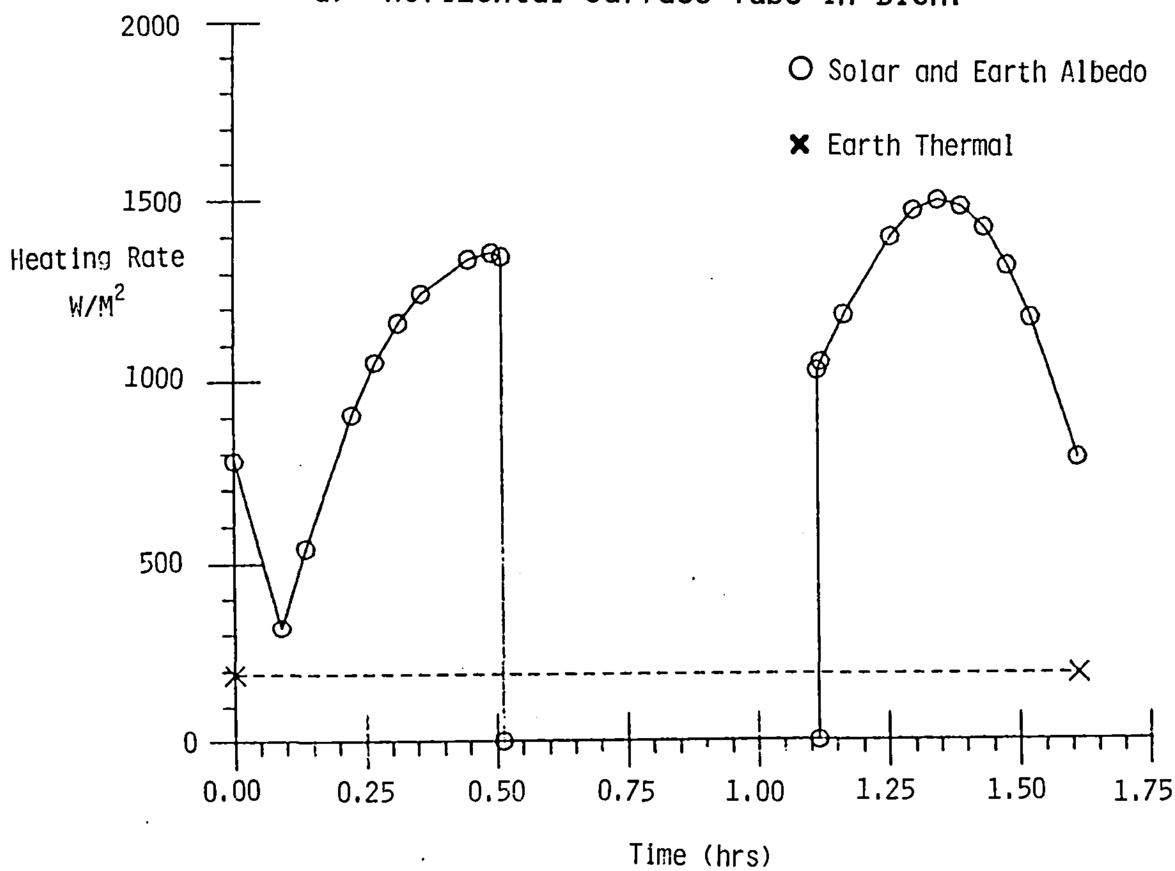


Figure 6. IDEAS Software.

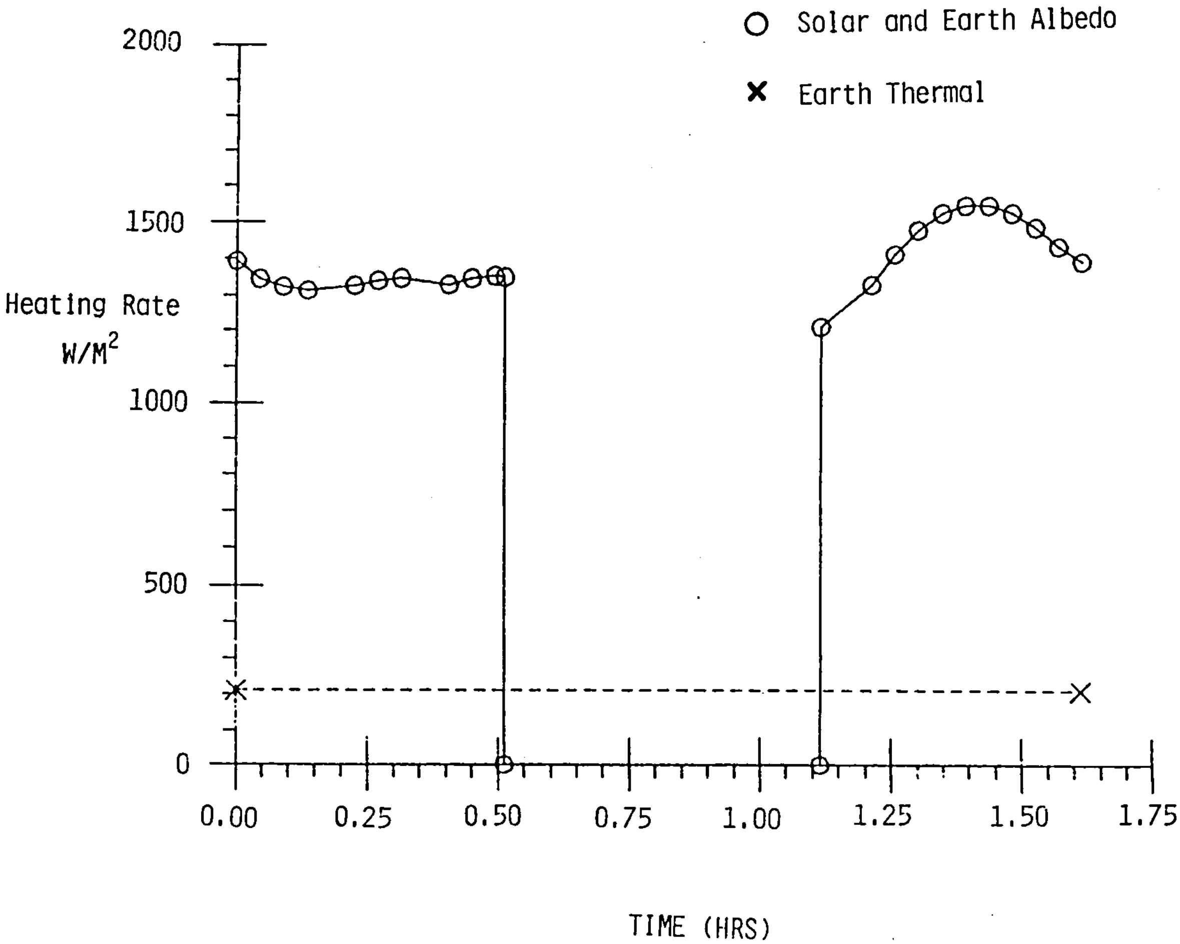


a) Horizontal Surface Tube in Dish.

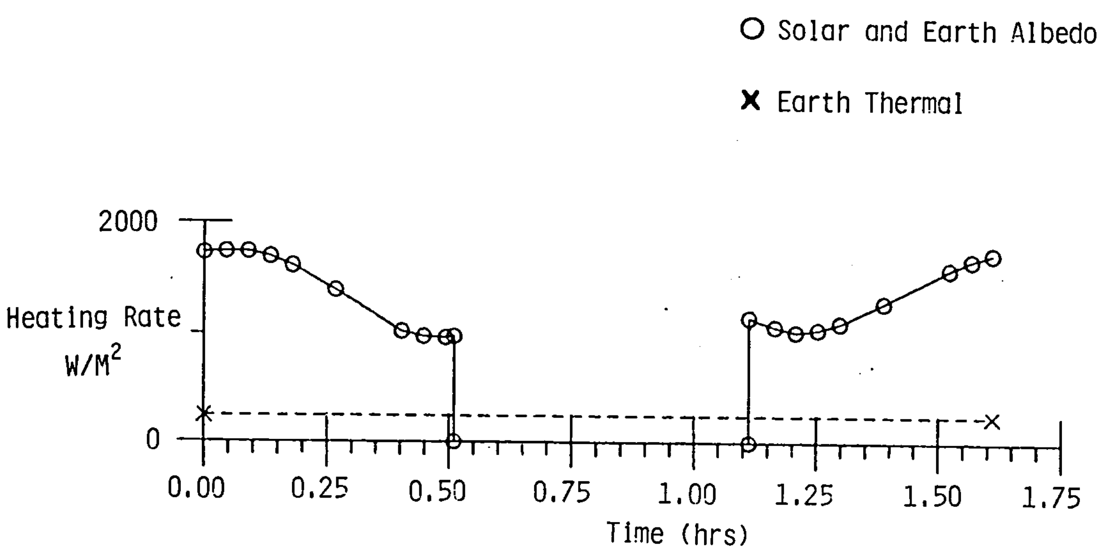


b) Vertical Tube in Feed Mast.

Figure 7. Structural Element Heating Rates.

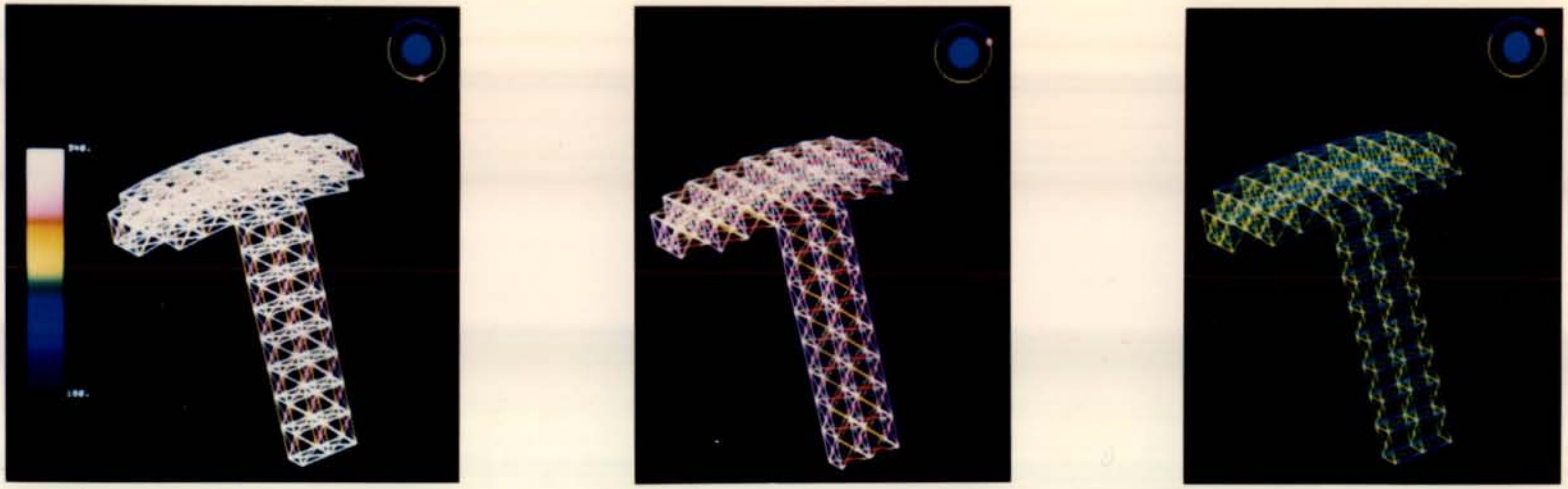


c) Horizontal Cable.



d) Vertical Cable.

Figure 7. Concluded.



(a) At the hottest point, $\Phi \approx 19°$.

(b) Just prior to entry into Earth's shadow, $\Phi = 112.5°$.

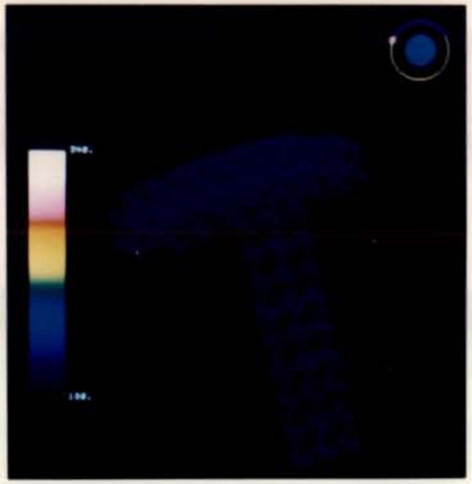
(c) Just after entry into Earth's shadow, $\Phi = 123.75°$.

(d) At midpoint of Earth's shadow, $\Phi = 180°$.

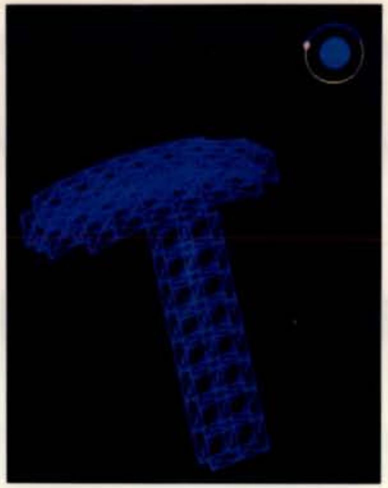
(e) Just prior to exit from Earth's shadow, $\Phi = 247.5°$.

(f) 5 minutes after exit from Earth's shadow, $\Phi = 270.4°$.

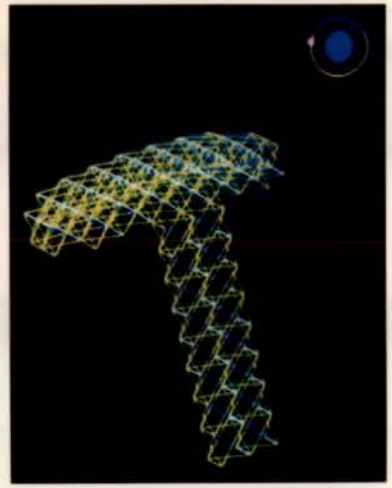
Fig. 8 Color graphic display of temperature data.



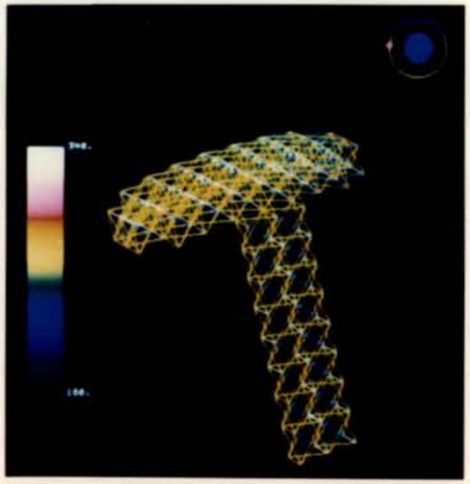
(a) Just prior to exit, $\Phi = 247.5°$.



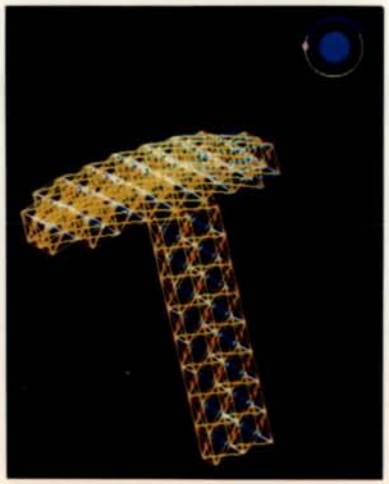
(b) 1 minute after exit, $\Phi = 254.4°$.



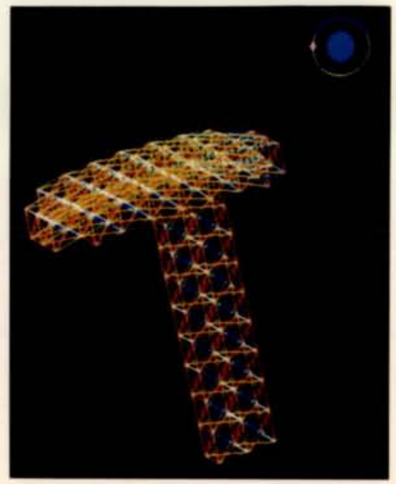
(c) 2 minutes after exit, $\Phi = 258.4°$.



(d) 3 minutes after exit, $\Phi = 262.4°$.



(e) 4 minutes after exit, $\Phi = 268.4°$.



(f) 5 minutes after exit, $\Phi = 270.4°$.

Fig. 9 Temperature data at exit from Earth's shadow.

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16. Abstract

A color video display technique is demonstrated as a tool for rapid determination of thermal problems during the preliminary design of complex space systems. A thermal analysis is presented for the lattice-structured Earth Observation Satellite (EOS) spacecraft at 32 points in a baseline non Sun-synchronous (60^{o} inclination) orbit. Large temperature variations (on the order of 150 K) were observed on the majority of the members. A gradual decrease in temperature was observed as the spacecraft traversed the Earth's shadow, followed by a sudden rise in temperature (100 K) as the spacecraft exited the shadow. Heating rate and temperature histories of selected members and color graphic displays of temperatures on the spacecraft are presented.

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